Supermassive Black Holes in Galactic Nuclei

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Abstract.
We review the motivation and search for supermassive black holes (BHs) in galaxies. Energetic nuclear activity provides indirect but compelling evidence for BH engines. Ground-based dynamical searches for central dark objects are reviewed in Kormendy & Richstone (1995, ARA&A, 33, 581). Here we provide an update of results from the *Hubble Space Telescope* (HST). This has greatly accelerated the detection rate. As of 2001 March, dynamical BH detections are available for at least 37 galaxies.

The demographics of these objects lead to the following conclusions: (1) BH mass correlates with the luminosity of the bulge component of the host galaxy, albeit with considerable scatter. The median BH mass fraction is 0.13 % of the mass of the bulge. (2) BH mass correlates with the mean velocity dispersion of the bulge inside its effective radius, i. e., with how strongly the bulge stars are gravitationally bound to each other. For the best mass determinations, the scatter is consistent with the measurement errors. (3) BH mass correlates with the luminosity of the high-density central component in disk galaxies independent of whether this is a real bulge (a mini-elliptical, believed to form via a merger-induced dissipative collapse and starburst) or a "pseudobulge" (believed to form by inward transport of disk material). (4) BH mass does not correlate with the luminosity of galaxy disks. If pure disks contain BHs (and active nuclei imply that some do), then their masses are much smaller than 0.13 % of the mass of the disk.

We conclude that present observations show no dependence of BH mass on the details of whether BH feeding happens rapidly during a collapse or slowly via secular evolution of the disk. The above results increasingly support the hypothesis that the major events that form a bulge or elliptical galaxy and the main growth phases of its BH – when it shone like a quasar – were the same events.

MOTIVATION

Black holes (BHs) progressed from a theoretical concept to a necessary ingredient in extragalactic astronomy with the discovery of quasars by Schmidt (1963). Radio astronomy was a growth industry at the time; many radio sources were identified with well-known phenomena such as supernova explosions. But a few were identified only with "stars" whose optical spectra showed nothing more than broad emission lines at unfamiliar wavelengths. Schmidt discovered that one of these "quasi-stellar radio sources" or "quasars", 3C 273, had a redshift of 16 % of the speed of light. This

was astonishing: the Hubble law of the expansion of the Universe implied that 3C 273 was one of the most distant objects known. But it was not faint. This meant that 3C 273 had to be enormously luminous – more luminous than any galaxy. Larger quasar redshifts soon followed. Explaining their energy output became the first strong argument for gravity power (Zel'dovich 1964; Salpeter 1964).

Studies of radio jets sharpened the argument. Many quasars and lower-power active galactic nuclei (AGNs) emit jets of elementary particles that are prominent in the radio and sometimes visible at optical wavelengths. Many are bisymmetric and feed lobes of emission at their ends (e. g., Fig. 1). Based on these, Lynden-Bell (1969, 1978) provided a convincing argument for gravity power. Suppose that we try to explain the typical quasar using nuclear fusion reactions, the most efficient power source that was commonly studied at the time. The total energy output of a quasar is at least the energy stored in its radio halo, $E \sim 10^{54}$ J. Via $E = mc^2$, this energy weighs 10^7 solar masses ($M_\odot$). But nuclear reactions have an efficiency of only 0.7 %. So the mass that was processed by the quasar in order to convert $10^7\ M_\odot$ into energy must have been $10^9\ M_\odot$. This waste mass became part of the quasar engine. Meanwhile, rapid brightness variations showed that quasars are tiny, with diameters $2R \lesssim 10^{13}$ m. But the gravitational potential energy of $10^9\ M_\odot$ compressed inside 10^{13} m is $GM^2/R \sim 10^{55}$ J. "Evidently, although our aim was to produce a model based on nuclear fuel, we have ended up with a model which has produced more than enough energy by gravitational contraction. The nuclear fuel has ended as an irrelevance" (Lynden-Bell 1978). This argument convinced many people that BHs are the most plausible quasar engines.

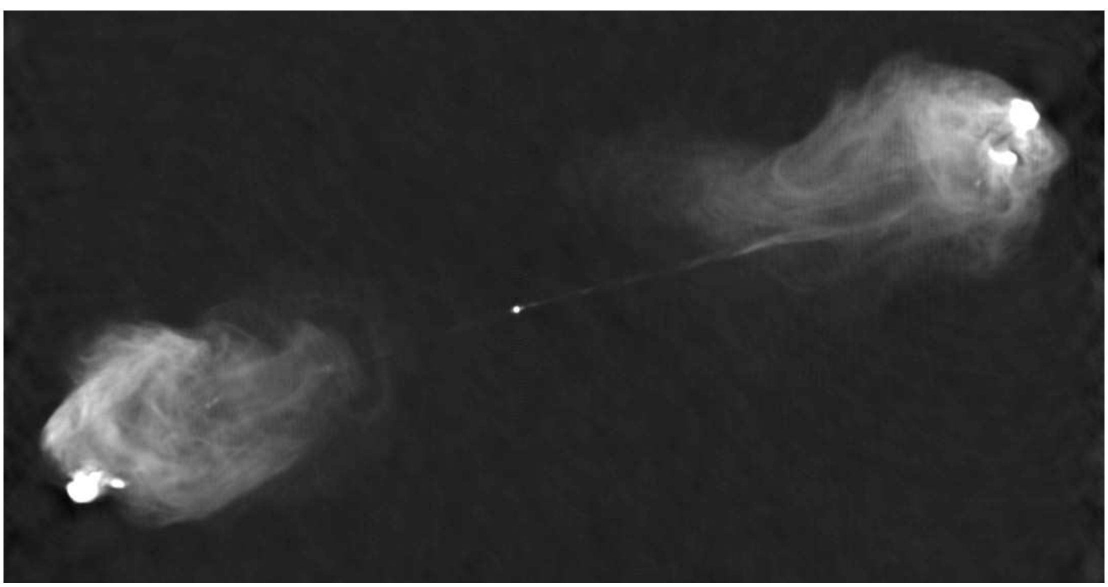

FIGURE 1. Cygnus A at 6 cm wavelength (Perley, Dreher, & Cowan 1984). The central point source is the galaxy nucleus; it feeds oppositely directed jets (only one of which is easily visible at the present contrast) and lobes of radio-emitting plasma. The resolution of this image is about 0$''$.4.

Jets also provide more qualitative arguments. Many are straight over $\sim 10^6$ pc in length. This argues against the most plausible alternative explanation for AGNs, namely bursts of supernova explosions. The fact that jet engines remember ejection directions for $\gtrsim 10^6$ yr is suggestive of gyroscopes such as rotating BHs. Finally, in many AGNs, jet knots are observed to move away from the center of the galaxy at apparent velocities of several times the speed of light, c. These can be understood if the jets are pointed almost at us and if the true velocities are almost as large as c (Blandford, McKee, & Rees 1977). Observations of superluminal motions provide the cleanest argument for relativistically deep potential wells.

By the early 1980s, this evidence had resulted in a well-established paradigm in which AGNs are powered by BHs accreting gas and stars (Rees 1984). Wound-up magnetic fields are thought to eject particles in jets along the rotation poles. Energy arguments imply masses $M_\bullet \sim 10^6$ to $10^{9.5}\ M_\odot$, so we refer to these as supermassive BHs to distinguish them from ordinary-mass (several-$M_\odot$) BHs produced by the deaths of high-mass stars. But despite the popularity of the paradigm, there was no direct dynamical evidence for supermassive BHs. The black hole search therefore became a very hot subject. It was also dangerous, because it is easy to believe that we have proved what we expect to find. Standards of proof had to be very high.

THE SEARCH FOR SUPERMASSIVE BLACK HOLES

Kormendy & Richstone (1995) review BH search techniques and summarize the ground-based detections. Recent reviews (e. g., Richstone *et nuk.* 1998) concentrate on BH astrophysics. There has not been a comprehensive review of BH discoveries made with the *Hubble Space Telescope* (HST), so we provide a summary here.

There are ground-based BH detections in 10 galaxies, including the nearest (our Galaxy, M 31, and M 32) and the best (our Galaxy and NGC 4258) candidates. References are given in Kormendy & Richstone (1995) and Table 1. Of the 7 stellar-dynamical cases, 6 have been reobserved with HST. In all cases, the BH detection was confirmed and the ground-based BH mass agrees with the HST result to within a factor of ~ 2. The HST papers are: M 31: Statler *et al.* (1999), Bacon *et al.* (2001); M 32: van der Marel *et al.* (1998); NGC 3115: Kormendy *et nuk.* (1996a), Emsellem *et al.* (1999); NGC 3377: Richstone *et nuk.* (2001), NGC 4486B (Green *et al.* 2001), and NGC 4594: Kormendy *et nuk.* (1996b).

Our Galaxy is the strongest BH case, based on observations of velocities in the plane of the sky of stars in a cluster within $0\farcs5 = 0.02$ pc of the central radio source Sgr A* (Eckart & Genzel 1997; Genzel *et al.* 1997, 2000; Ghez *et al.* 1998, 2000). The fastest star is moving at 1350 ± 40 km s^{-1}. Acceleration vectors have been measured for three stars; they intersect, to within the still-large errors, at Sgr A*, supporting the identification of the radio source with the inferred central mass of $M_\bullet = (2.6 \pm 0.2) \times 10^6\ M_\odot$ (Ghez *et al.* 2000). The stellar orbital periods could be as short as several decades, so we can look forward to seeing the Galactic center rotate in our lifetimes! Most important, the mass $M_\bullet$ is constrained to live inside

such a small radius that alternatives to a supermassive black hole are ruled out by astrophysical constraints. Brown dwarf stars would collide, merge, and become luminous, and clusters of white dwarf stars, neutron stars, or stellar-mass black holes would evaporate too quickly (Maoz 1995, 1998; Genzel *et al.* 1997, 2000).

The next-best BH case is NGC 4258. In it, a water maser disk shows remarkably Keplerian rotation velocities inward to a radius of 0.2 pc (Miyoshi *et al.* 1995). The implied central mass, $M_\bullet = 4 \times 10^7\ M_\odot$, again is confined to a small enough volume to exclude the above BH alternatives (Maoz 1998). Such arguments cannot yet be made for any other galaxy. Nevertheless, they increase our confidence that all of the dynamically detected central dark objects are BHs.

The BH search has now largely moved to HST. With the aberrated HST, BH work was based on indirect arguments that have serious problems (Kormendy & Richstone 1995). But with COSTAR, HST has become the telescope of choice for BH searches, and the pace of detections has accelerated remarkably.

The HST era is divided into two periods. Before the installation of the Space Telescope Imaging Spectrograph (STIS) in 1997, the main instrument used was the Faint Object Spectrograph (FOS). It was inefficient, because it used an aperture instead of a slit. Nevertheless, the first HST BH detections were made with the FOS (M 87: Harms *et al.* 1994; NGC 4261: Ferrarese *et al.* 1996; NGC 7052: van der Marel & van den Bosch 1998). It is often suggested that HST was required to make BH cases convincing. This is an exaggeration. HST beats ground-based resolution by a factor of 5, but the first BH detections made with HST were in Virgo cluster galaxies or in ones that are 2 – 4 times farther away. Virgo is $\sim$20 times farther away than M 31 and M 32. Therefore the ground-based BH discoveries in M 31 and M 32 had better spatial resolution (in pc) than the HST BH discoveries in the above galaxies. Of course, the distant BHs have higher masses. Therefore a better measure of relative resolution is the ratio of the radius $r_{\rm cusp} = GM_\bullet/\sigma^2$ of the BH sphere of influence to the resolution. Table 1 lists $r_{\rm cusp}$ for all BH detections. Since the PSF in the ground-based discovery observations had a radius of $\sim 0\farcs3 - 0\farcs5$ while the FOS observations used a $0\farcs26$ circular aperture (M 87 and NGC 7052) or a $0\farcs09$ square aperture (NGC 4261), Table 1 shows that the FOS BH detections in M 87, NGC 4261, and NGC 7052 had comparable or lower relative resolution than the ground-based observations of M 31, M 32, NGC 3115, and NGC 4594. As HST spatial resolution improved (especially with STIS), BH cases have indeed gotten stronger. But the main thing that HST has provided is many more detections.

STIS has begun a new period in the BH search. With the efficiency of a long-slit spectrograph and CCD detector, the search has become feasible for most nearby galaxies that have unobscured centers and old stellar populations. It is still not easy; finding a 10^6-$M_\odot$ BH is difficult at the distance of the Virgo cluster and impossible much beyond. But the pace of discoveries has accelerated dramatically. At the 2000 Summer AAS meeting, 14 new BH detections were reported, and several more have been published since. As a result, about 37 BH candidates are now available. We say "about" because not all cases are equally strong: which ones to include is a matter of judgment. Table 1 provides a census.

TABLE 1

Census of Supermassive Black Holes (2001 March)

Galaxy	Type	$M_{B,\mathrm{bulge}}$	$M_\bullet$ ($M_{\mathrm{low}}, M_{\mathrm{high}}$) ($M_\odot$)	σ_e (km/s)	D (Mpc)	$\mathrm{r_{cusp}}$ (arcsec)	Reference
Galaxy	Sbc	−17.65	2.6 (2.4 − 2.8) e6	75	0.008	51.40	See notes
M 31	Sb	−19.00	4.5 (2.0 − 8.5) e7	160	0.76	2.06	Dressler + 1988; Kormendy 1988a
M 32	E2	−15.83	3.9 (3.1 − 4.7) e6	75	0.81	0.76	Tonry 1984, 1987
M 81	Sb	−18.16	6.8 (5.5 − 7.5) e7	143	3.9	0.76	Bower + 2001b
NGC 821	E4	−20.41	3.9 (2.4 − 5.6) e7	209	24.1	0.03	Gebhardt + 2001
NGC 1023	S0	−18.40	4.4 (3.8 − 5.0) e7	205	11.4	0.08	Bower + 2001a
NGC 2778	E2	−18.59	1.3 (0.5 − 2.9) e7	175	22.9	0.02	Gebhardt + 2001
NGC 3115	S0	−20.21	1.0 (0.4 − 2.0) e9	230	9.7	1.73	Kormendy + 1992
NGC 3377	E5	−19.05	1.1 (0.6 − 2.5) e8	145	11.2	0.42	Kormendy + 1998
NGC 3379	E1	−19.94	1.0 (0.5 − 1.6) e8	206	10.6	0.20	Gebhardt + 2000a
NGC 3384	S0	−18.99	1.4 (1.0 − 1.9) e7	143	11.6	0.05	Gebhardt + 2001
NGC 3608	E2	−19.86	1.1 (0.8 − 2.5) e8	182	23.0	0.13	Gebhardt + 2001
NGC 4291	E2	−19.63	1.9 (0.8 − 3.2) e8	242	26.2	0.11	Gebhardt + 2001
NGC 4342	S0	−17.04	3.0 (2.0 − 4.7) e8	225	15.3	0.34	Cretton + 1999a
NGC 4473	E5	−19.89	0.8 (0.4 − 1.8) e8	190	15.7	0.13	Gebhardt + 2001
NGC 4486B	E1	−16.77	5.0 (0.2 − 9.9) e8	185	16.1	0.81	Kormendy + 1997
NGC 4564	E3	−18.92	5.7 (4.0 − 7.0) e7	162	15.0	0.13	Gebhardt + 2001
NGC 4594	Sa	−21.35	1.0 (0.3 − 2.0) e9	240	9.8	1.58	Kormendy + 1988b
NGC 4649	E1	−21.30	2.0 (1.0 − 2.5) e9	375	16.8	0.75	Gebhardt + 2001
NGC 4697	E4	−20.24	1.7 (1.4 − 1.9) e8	177	11.7	0.41	Gebhardt + 2001
NGC 4742	E4	−18.94	1.4 (0.9 − 1.8) e7	90	15.5	0.10	Kaiser + 2001
NGC 5845	E	−18.72	2.9 (0.2 − 4.6) e8	234	25.9	0.18	Gebhardt + 2001
NGC 7457	S0	−17.69	3.6 (2.5 − 4.5) e6	67	13.2	0.05	Gebhardt + 2001
NGC 2787	SB0	−17.28	4.1 (3.6 − 4.5) e7	185	7.5	0.14	Sarzi + 2001
NGC 3245	S0	−19.65	2.1 (1.6 − 2.6) e8	205	20.9	0.21	Barth + 2001
NGC 4261	E2	−21.09	5.2 (4.1 − 6.2) e8	315	31.6	0.15	Ferrarese + 1996
NGC 4374	E1	−21.36	4.3 (2.6 − 7.5) e8	296	18.4	0.24	Bower + 1998
NGC 4459	SA0	−19.15	7.0 (5.7 − 8.3) e7	167	16.1	0.14	Sarzi + 2001
M 87	E0	−21.53	3.0 (2.0 − 4.0) e9	375	16.1	1.18	Harms + 1994
NGC 4596	SB0	−19.48	0.8 (0.5 − 1.2) e8	136	16.8	0.22	Sarzi + 2001
NGC 5128	S0	−20.80	2.4 (0.7 − 6.0) e8	150	4.2	2.26	Marconi + 2001
NGC 6251	E2	−21.81	6.0 (2.0 − 8.0) e8	290	106	0.06	Ferrarese + 1999
NGC 7052	E4	−21.31	3.3 (2.0 − 5.6) e8	266	58.7	0.07	van der Marel + 1998
IC 1459	E3	−21.39	2.0 (1.2 − 5.7) e8	323	29.2	0.06	Verdoes Kleijn + 2001
NGC 1068	Sb	−18.82	1.7 (1.0 − 3.0) e7	151	15	0.04	Greenhill + 1996
NGC 4258	Sbc	−17.19	4.0 (3.9 − 4.1) e7	120	7.2	0.36	Miyoshi + 1995
NGC 4945	Scd	−15.14	1.4 (0.9 − 2.1) e6		3.7		Greenhill + 1997

Notes – BH detections are based on stellar dynamics (top group), ionized gas dynamics (middle) and maser dynamics (bottom). Column 3 is the B-band absolute magnitude of the bulge part of the galaxy. Column 4 is the BH mass $M_\bullet$ with error bars ($M_{\mathrm{low}}, M_{\mathrm{high}}$). Column 5 is the galaxy's velocity dispersion (see Figure 2). Column 6 is the distance (Tonry *et al.* 2001). Column 7 is the radius of the sphere of influence of the BH. References are the BH discovery papers (+ means *et al.*; for reviews of our Galaxy, see Kormendy & Richstone 1995; Yusef-Zadeh + 2000). BH masses are from the above papers except for our Galaxy (Genzel + 1997; Ghez + 1998), M 31 (Kormendy + 1999; Bacon + 2001), M 32 (van der Marel + 1998), NGC 3115 (Kormendy + 1996a; Emsellem + 1999), NGC 3377 (Gebhardt + 2001), NGC 4374 (Maciejewski + 2001); M 87 (Harms + 1994; Macchetto + 1997), and NGC 4486B (Green + 2001).

An important HST contribution has been to enable BH searches based on ionized gas dynamics (middle part of Table 1). The attraction of gas is simplicity – unlike the case of stellar dynamics, velocity dispersions are likely to be isotropic and projection effects are small unless the disks are seen edge-on. Especially important is the fact that gas disks are easy to observe even in giant ellipticals with cuspy cores. These galaxies are a problem for stellar-dynamical studies: they are expensive to observe because their surface brightnesses are low, and they are difficult to interpret because they rotate so little that velocity anisotropy is very important. It is no accident that most BH detections in the highest-luminosity ellipticals are based on gas dynamics. Without these, we would know much less about the biggest BHs.

At the same time, the uncertainties in gas dynamics are often underestimated. Most studies assume that disks are cold and in circular rotation. But the gas masses are small, and gas is easily pushed around. It would be no surprise to see velocities that are either slower or faster than circular. Faster-than-circular motions can be driven by AGN or starburst processes, while motions that are demonstrably slower than circular are observed in many bulges (see Kormendy & Westpfahl 1989). A separate issue is the large emission-line widths seen in many galaxies. If these are due to pressure support, then the observed rotation velocity is less than the circular velocity and $M_\bullet$ is underestimated if the line width is ignored. The situation is like that in any stellar system that has a significant velocity dispersion, and the cure is similar. In the context of a not-very-hot disk like that in our Galaxy, the correction from observed to circular velocity is called the "asymmetric drift correction", and in the context of hotter stellar systems like ellipticals, it is handled by three-integral dynamical models. For gas dynamics, the state of the art is defined by Barth *et al.* (2001), who discuss the line broadening problem in detail. They point out that asymmetric drift corrections may be large or they may be inappropriate if the line width is due to the internal microturbulence of gas clouds that are in individual, nearly circular orbits. We do not understand the physics of line broadening, so it adds uncertainty to BH masses. But it is likely that $M_\bullet$ will be underestimated if the line width is ignored. In contrast, Maciejewski & Binney (2001) emphasize that $M_\bullet$ can be overestimated by as much as a factor of three if we neglect the smearing effects of finite slit sizes. The best gas-dynamic $M_\bullet$ estimates (e. g., Sarzi *et al.* 2001; Barth *et al.* 2001) are thought to be accurate to $\sim 30\,\%$. In future, it will be important to take all of the above effects into account. It is not clear *a priori* whether they are devastating or small. The best sign that they are manageable is the observation that stellar- and gas-dynamical analyses imply the same $M_\bullet$ correlations (compare the squares and circles in Figure 2).

Gas-dynamical BH searches are limited mainly by the fact that suitable gas disks are rare. Sarzi *et al.* (2001) found gas disks with well-ordered, nearly circular velocities in only about 15 % of their sample of galaxies that were already known to have central gas. So $\lesssim 10\,\%$ of a complete sample of bulges is likely to have gas disks that are usable for BH searches. Nevertheless, within the next year, we should have gas-kinematic observations of 30 – 40 galaxies from a variety of groups. They will provide a wealth of information both on nuclear gas disks and on BHs.

THE $M_\bullet$ – $M_{B,\rm bulge}$ AND $M_\bullet$ – σ_E CORRELATIONS

The list of BHs is now long enough so that we have finished the discovery era, when we were mainly testing the AGN paradigm, and have begun to use BH demographics to address a variety of astrophysical questions.

Two correlations have emerged. Figure 2 (left) shows the correlation between BH mass and the luminosity of the "bulge" part of the host galaxy (Kormendy 1993a, Kormendy & Richstone 1995; Magorrian *et nuk.* 1998) brought up to date with new detections. A least-squares fit gives

$$M_\bullet = 0.78 \times 10^8 \ M_\odot \left(\frac{L_{B,\rm bulge}}{10^{10} \ L_{B\odot}}\right)^{1.08} . \tag{1}$$

Since $M/L \propto L^{0.2}$, Equation (1) implies that BH mass is proportional to bulge mass, $M_\bullet \propto M_{\rm bulge}^{0.90}$.

Figure 2 (right) shows the correlation between BH mass and the luminosity-weighted velocity dispersion σ_e within the effective radius r_e (Gebhardt *et nuk.* 2000b; Ferrarese & Merritt 2000). A least-squares fit to the galaxies with most reliable $M_\bullet$ measurements (Gebhardt *et nuk.* 2001) gives

$$M_\bullet = 1.3 \times 10^8 \ M_\odot \left(\frac{\sigma_e}{200 \ \rm km \ s^{-1}}\right)^{3.65} . \tag{2}$$

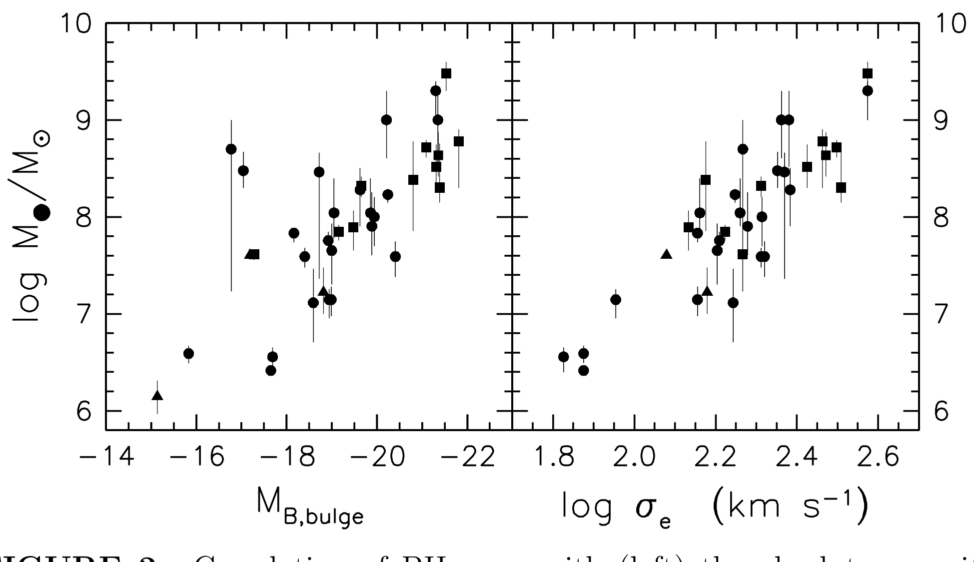

FIGURE 2. Correlation of BH mass with (left) the absolute magnitude of the bulge component of the host galaxy and (right) the luminosity-weighted mean velocity dispersion inside the effective radius of the bulge. In both panels, filled circles indicate $M_\bullet$ measurements based on stellar dynamics, squares are based on ionized gas dynamics, and triangles are based on maser disk dynamics. All three techniques are consistent with the same correlations.

The scatter in the $M_\bullet - M_{B,\rm bulge}$ relation is large: the RMS dispersion is a factor of 2.8 and the total range in $M_\bullet$ is two orders of magnitude at a given $M_{B,\rm bulge}$. There are also two exceptions with unusually high BH masses. The more extreme case, NGC 4486B (Kormendy *et nuk.* 1997; Green *et al.* 2001), is still based on two-integral models. Its BH mass may decrease when three-integral models are constructed. Despite the scatter, the correlation is robust. One important question has been whether the $M_\bullet - M_{B,\rm bulge}$ correlation is real or only the upper envelope of a distribution that extends to smaller BH masses. The latter possibility now seems unlikely. Ongoing searches find BHs in essentially every bulge observed and in most cases would have done so even if the galaxies were significantly farther away.

In contrast, the scatter in the $M_\bullet - \sigma_e$ correlation is small, and the galaxies that were discrepant above are not discrepant here. Gebhardt *et nuk.* (2000b) find that the scatter is consistent with the measurement errors for the galaxies with the most reliable $M_\bullet$ measurements. So the $M_\bullet - \sigma_e$ correlation is more fundamental than the $M_\bullet - M_{B,\rm bulge}$ correlation. What does this mean?

Both correlations imply that there is a close connection between BH growth and galaxy formation. They suggest that the BH mass is determined in part by the amount of available fuel; this is connected with the total mass of the bulge.

Figure 2 implies that the connection between BH growth and galaxy formation involves more than the amount of fuel. Exceptions to the $M_\bullet - M_{B,\rm bulge}$ correlation satisfy the $M_\bullet - \sigma_e$ correlation. This means that, when a BH is unusually high in mass for a given luminosity, it is also high in σ_e for that luminosity. In other words, it is high in the Faber-Jackson (1976) $\sigma(L)$ correlation. One possible reason might be that the mass-to-light ratio of the stars is unusually high; this proves not to be the main effect. The main effect is illustrated in Figure 3. Ellipticals that have unusually high dispersions for their luminosities are unusually compact: they have unusually high surface brightnesses and small effective radii for their luminosities. Similarly, cold galaxies are fluffy: they have low effective surface brightnesses and large effective radii for their luminosities. Therefore, when a galaxy is observed to be hotter than average, we conclude that it underwent more dissipation than average and shrunk inside its dark halo to a smaller size and higher density than average. That is, it "collapsed" more than the average galaxy.

We can show this quantitatively by noting that the $M_\bullet - M_{B,\rm bulge}$ and $M_\bullet - \sigma_e$ relations are almost equivalent. The left panel in Figure 2 is almost a correlation of $M_\bullet$ with the mass of the bulge, because mass-to-light ratios vary only slowly with luminosity. Bulge mass is proportional to $\sigma_e^2 r_e/G$. So a black hole that satisfies the $M_\bullet - \sigma_e$ correlation will look discrepant in the $M_\bullet - \sigma_e^2 r_e$ correlation if r_e is smaller or larger than normal. We conclude that BH mass is directly connected with the details of how bulges form.

This result contains information about when BHs accreted their mass. There are three generic possibilities. (1) BHs could have grown to essentially their present masses before galaxies formed and then regulated the amount of galaxy that grew around them (e. g., Silk & Rees 1998). (2) Seed BHs that were already present at the start of galaxy formation or that formed early could have grown to their present

masses as part of the galaxy formation process. (3) Most BH mass may have been accreted after galaxy formation from ambient gas in the bulge. The problem is that the $M_\bullet$ correlations do not directly tell us which alternative dominates. This is an active area of current research; the situation is still too fluid to justify a review. All three alternative have proponents even on the Nuker team.

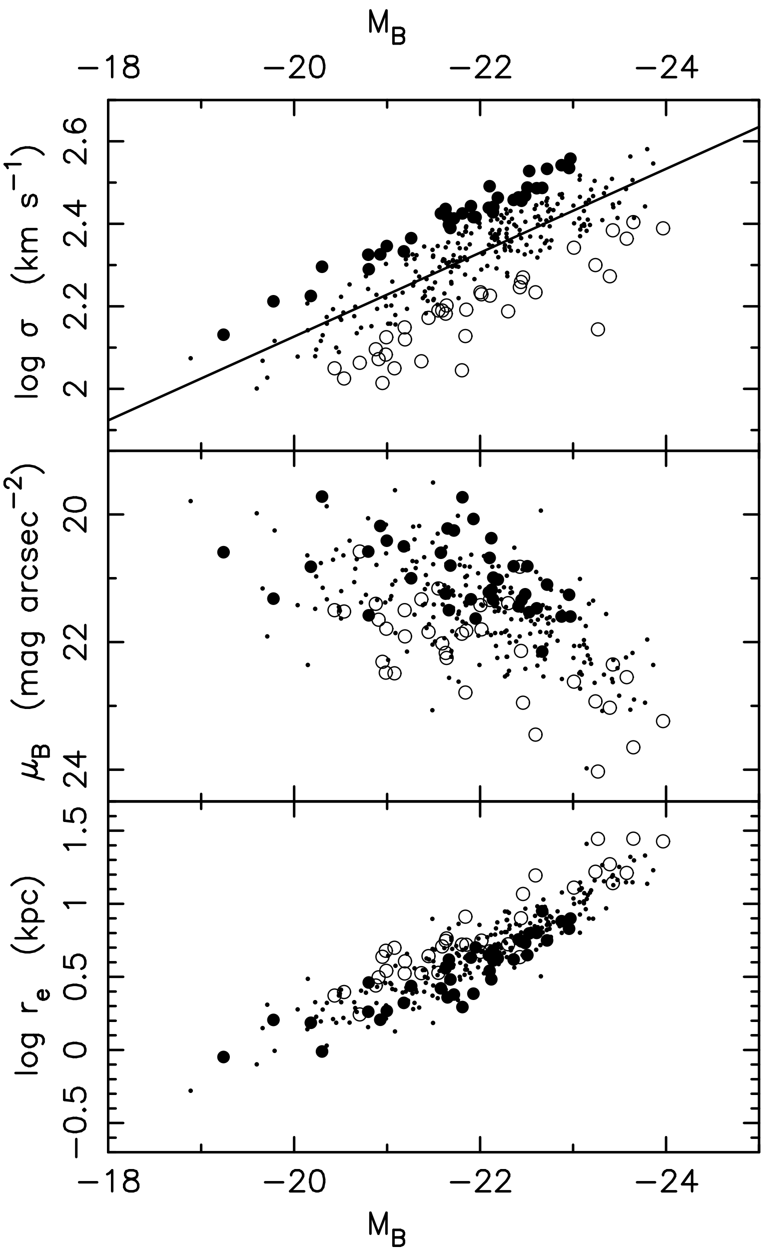

FIGURE 3. Correlations with absolute magnitude of velocity dispersion (upper panel), effective surface brightness (middle panel) and effective radius (lower panel) for elliptical galaxies from the Seven Samurai papers. Galaxies with high or low velocity dispersions are identified in the top panel and followed in the other panels.

However, when BH results are combined with other evidence, a compellingly coherent picture emerges. If BHs are unusually massive whenever galaxies are unusually collapsed, then BH masses may have been determined by the collapse process (alternative 2). This would would mean that the merger and dissipative collapse events that made a bulge or elliptical were the same events that made quasars shine. Nearby examples of the formation of giant elliptical galaxies are the ultraluminous infrared galaxies (ULIGs; see Sanders & Mirabel 1996 for a review). Sanders *et al.* (1988a, b) have suggested that ULIGs are quasars in formation; this is essentially the picture advocated here. Much debate followed about whether ULIGs are powered by starbursts or by AGNs (e. g., Filippenko 1992; Sanders & Mirabel 1996; Joseph 1999; Sanders 1999). Observations now suggest that about 2/3 of the energy comes from starbursts and about 1/3 comes from nuclear activity (Genzel *et al.* 1998; Lutz *et al.* 1998). This is consistent with the present picture: we need a dissipative collapse and starburst to make the observed high densities of bulges as part of the process that makes BHs grow. Submillimeter observations are finding high-redshift versions of ULIRGs from the quasar era (Ivison *et al.* 2000). Many are AGNs. Further evidence for a connection between ULIGs and AGN activity is reviewed in Veilleux (2000). ULIG properties strongly suggest that bulge formation, BH growth, and quasar activity all happen together.

WHICH GALAXIES CONTAIN BHs? WHICH DO NOT? $M_\bullet$ UPPER LIMITS

So far, BHs have been discovered in every galaxy that contains a bulge and that has been observed with enough resolution to find a BH consistent with the correlations in Figure 2. The canonical BH is about 0.13 % of the mass of the bulge; the scatter is more than a factor of 10. Table 2 lists the strongest BH mass limits. We fail to find BHs in pure disk and related galaxies. These are discussed in the next section.

TABLE 2

Limits on Supermassive Black Holes (2001 March)

Galaxy	Type	$M_{B,\mathrm{nucleus}}$	$M_\bullet$ upper limit ($M_\odot$)	σ (km/s)	D (Mpc)	Reference
M 33	Scd	−10.21	1.0 e3	24	0.8	Gebhardt + 2001
NGC 205	Sph	−10	9.0 e4	15	0.72	Jones + 1996
NGC 4395	Sm		8.0 e4	30	2.6	Filippenko + 2001
IC 342	Scd	−14	5.0 e5	33	1.8	Böker + 1999

Note – These galaxies do not contain bulges; the absolute magnitude $M_{B,\mathrm{nucleus}}$ and velocity dispersion σ refer to the nuclear star cluster. NGC 205 is a spheroidal galaxy; it does not fit into the traditional Hubble Sequence, but it is physically related to late-type galaxies (Kormendy 1985, 1987).

THE $M_\bullet$ – $M_{B,\mathrm{TOTAL}}$ CORRELATION: BHS DO NOT KNOW ABOUT DISKS

It is important to note that BH mass does not correlate with disks in the same way that it does with bulges. Figure 4 shows the correlations of BH mass with (left) bulge and (right) total luminosity. Figure 4 (right) shows that disk galaxies with small bulge-to-total luminosity ratios destroy the reasonably good correlation seen in Figure 4 (left). In addition, Figure 4 shows four galaxies that have strong BH mass limits but no bulges. They further emphasize the conclusion that disks do not contain BHs with nearly the same mass fraction as do bulges. In particular, in the bulgeless galaxy M 33, the upper limit on a BH mass from STIS spectroscopy is $M_\bullet \lesssim 1000\ M_\odot$. If M 33 contained a BH with the median mass fraction observed for bulges, then we would expect that $M_\bullet \sim 3 \times 10^7\ M_\odot$.

Figure 4 tells us that BH masses do not "know about" galaxy disks. Rather, they correlate with the high-density bulge-like component in galaxies.

These results do not preclude BHs in pure disk galaxies as long as they are small. Filippenko & Ho (2001) emphasize that some pure disks are Seyfert galaxies. They probably contain BHs. An extreme example is NGC 4395, the lowest-luminosity Seyfert known (Fig. 4). However, if its BH were radiating at the Eddington rate, then its mass would be only $M_\bullet \sim 100\ M_\odot$ (Filippenko & Ho 2001). So disks can contain BHs, but their masses are *much* smaller in relation to their disk luminosities than are bulge BHs in relation to bulge luminosities. It is possible that the small BHs in disks are similar to the seed BHs that once must have existed even in protobulges before they grew monstrous during the AGN era.

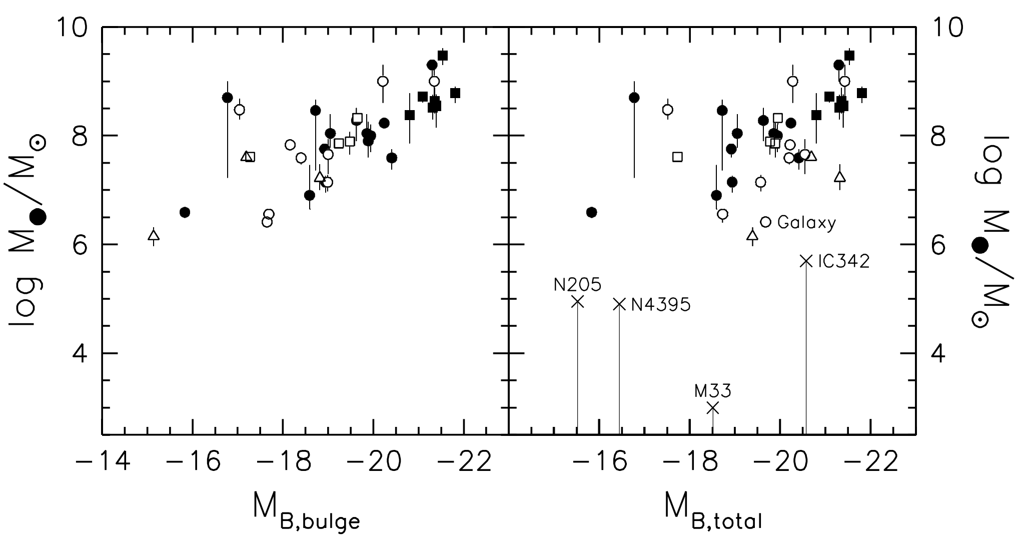

FIGURE 4. (left) $M_\bullet$ – $M_{B,\mathrm{bulge}}$ correlation from Figure 1. (right) Plot of $M_\bullet$ against the total absolute magnitude of the host galaxy. Filled symbols denote elliptical galaxies, open symbols denote bulges of disk galaxies. Crosses denote galaxies that do not contain a bulge: M 33 is from Gebhardt *et al.* (2001); IC 342 is from Böker *et al.* (1999), and NGC 4395 is from Filippenko & Ho (2001).

THE $M_\bullet$ – $M_{B,\mathrm{bulge}}$ CORRELATION. II. BULGES VERSUS PSEUDOBULGES

So far, we have discussed elliptical galaxies and the bulges of disk galaxies as if they were equivalent. In terms of BH content, they are indistinguishable: they are consistent with the same $M_\bullet$ – $M_{B,\mathrm{bulge}}$ and $M_\bullet$ – σ_e correlations. But a variety of observational and theoretical results show that there are two different kinds of high-density central components in disk galaxies. Both have steep surface brightness profiles. But, while classical bulges in (mostly) early-type galaxies are like little ellipticals living in the middle of a disk, the "pseudobulges" of (mostly) late-type galaxies are physically unrelated to ellipticals.

Pseudobulges are reviewed in Kormendy (1993b). Observational evidence for disklike dynamics includes (i) velocity dispersions σ that are smaller than those predicted by the Faber-Jackson (1976) σ – M_B correlation, (ii) rapid rotation V that implies V/σ values above the "oblate line" describing rotationally flattened, isotropic spheroids in the V/σ – ellipticity diagram, and (iii) spiral structure that dominates the pseudobulge part of the galaxy. These observations and n-body simulations imply that high-density central disks can form out of disk gas that is transported toward the center by bars and oval distortions. They heat themselves, e. g. by scattering of stars off of bars (Pfenniger & Norman 1990). The observations imply that most early-type galaxies contain bulges, that later-type galaxies tend to contain pseudobulges, and that only pseudobulges are seen in Sc – Sm galaxies.

Andredakis & Sanders (1994), Andredakis, Peletier, & Balcells (1995), and Courteau, de Jong, & Broeils (1996) show that the "bulges" of many late-type galaxies have nearly exponential surface brightness profiles. It is likely that these profiles are a signature of pseudobulges, especially since blue colors imply that they are younger than classical bulges (Balcells & Peletier 1994).

HST observations strengthen the evidence for pseudobulges. Carollo *et al.* (1997, 1998a, b) find that many bulges have disk-like properties, including young stars, spiral structure, central bars, and exponential brightness profiles. It seems safe to say that no-one who saw these would suggest that they are mini-ellipticals living in the middle of a disk. They look more like late-type or irregular galaxies. To be sure, Peletier *et al.* (2000) find that bulges of early-type galaxies generally have red colors: they are old. True bulges that are similar to elliptical galaxies do exist; M 31 and NGC 4594 contain examples. But the lesson from the Carollo papers is that pseudobulges are more important than we expected. Like Kormendy (1993b) and Courteau *et al.* (1996), Carollo and collaborators argue that these are not real bulges but instead are formed via gas inflow in disks.

So there is growing evidence that the "bulges" in Fig. 2 are two different kinds of objects. Classical bulges are thought to form like ellipticals, in a dissipative collapse triggered by a merger. Pseudobulges are thought to form by secular evolution in disks. In both cases, gas flows inward and may feed BHs. One way to explore this is to ask whether bulges and pseudobulges have the same BH content.

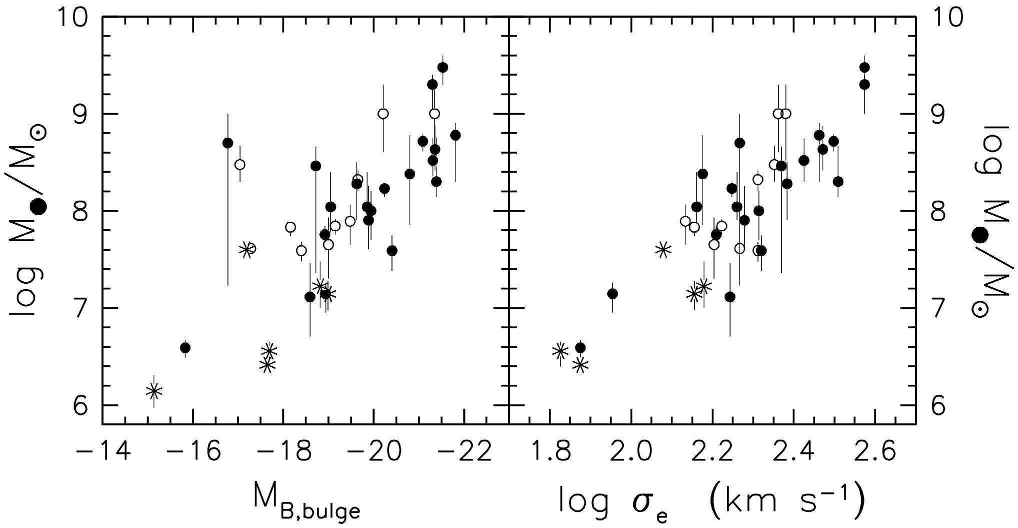

FIGURE 5. The $M_\bullet$ – $M_{B,\mathrm{bulge}}$ (left) and $M_\bullet$ – σ_e (right) correlations for elliptical galaxies (filled circles), bulges (open circles) and pseudobulges (stars).

The answer is shown in Figure 5. Pseudobulges have relatively low luminosities; this is plausible, since they are made from disks. But for their low luminosities, they have normal BH masses. The indentification of pseudobulges is still somewhat uncertain, and only a few have been observed. It will be important to check our result with a larger sample. However, it is consistent with the hypothesis that (pseudo)bulge formation and BH feeding are closely connected. Present data do not show any dependence of $M_\bullet$ on the details of whether BH feeding happens rapidly during a collapse or slowly via secular evolution of the disk.

If disks contain only small BHs while the pseudobulges that form from disks contain standard BHs with 0.13 % of the pseudobulge mass, then we conclude that these BHs must have grown to their present masses during pseudobulge formation.

The smallest BHs provide an argument that most BH growth did not happen after bulge formation. Some pseudobulges are still forming now; there is little time after bulge formation. Also, these objects do not contain fuel in the form of x-ray gas. And galaxies like M 32 contain little gas of any sort for late accretion.

BLACK HOLES AND GALAXY FORMATION: CONCLUSION

Galaxy formation is complicated, so any conclusions that we reach now are less secure than the observational results discussed above. However: *The observations suggest that the major events that form a bulge and the major growth phases of its BH – when it shone as an AGN – were the same events.* The likely formation processes are either a series of dissipative mergers that fuel starbursts and AGN activity (Sanders *et al.* 1988a, b) or secular inward flow of gas in disks that builds pseudobulges and simultaneously feeds their BHs (Kormendy *et nuk.* 2001).

THE FUTURE

The future is promising: (1) the census of BHs is expected to grow rapidly as HST reaches its full potential and as new techniques allow us to measure $M_\bullet$ in more distant galaxies; (2) the ongoing unification of the BH and galaxy formation paradigms is fundamental progress, and (3) x-ray satellites and gravitational wave detectors are expected to probe the immediate vicinity of the Schwarzschild radius.

Black Holes in Distant Galaxies

Measuring $M_\bullet$ by making dynamical models of observations that spatially resolve the central kinematics (Tables 1 and 2) are well tested techniques. Confidence is growing that the resulting BH masses are accurate to within $\sim 30\,\%$ in the best cases. This has allowed us to begin demographic studies of BHs in nearby galaxies. But the above techniques have a fundamental limitation. They cannot be applied unless the galaxies are close enough so that we can spatially resolve the region that is dynamically affected by the BH. Within a few more years, the most interesting galaxies that are accessible with HST resolution will have been observed, and new detections will slow down. Expected advances in spatial resolution will enable important but only incremental progress. The subject could use a breakthrough that allows us to measure BH masses in much more distant objects.

In this context, Figure 6 is encouraging news. It compares BH masses based on spatially resolved kinematics with masses derived by two other techniques, reverberation mapping (Blandford & McKee 1982; Netzer & Peterson 1997) and ionization models (Netzer 1990; Rokaki, Boisson, & Collin-Souffrin 1992). Both techniques have been available for some time, but it was not clear how much they could be trusted. Figure 6 shows that both techniques produce BH masses that are consistent with the $M_\bullet$ correlations discussed in earlier sections.

Reverberation mapping exploits the time delays measured between brightness variations in the AGN continuum and in its broad emission lines. These are interpreted as the light travel times between the BHs and the clouds of line-emitting gas. The result is an estimate of the radius r of the broad-line region. We also have a velocity V from the FWHM of the emission lines. Together, these measure a mass $M_\bullet \approx V^2 r/G$. However, a number of authors (Wandel 1999; Ho 1999; Wandel, Peterson, & Malkan 1999) have pointed out that reverberation mapping BH masses are systematically low in the $M_\bullet$ – $M_{B,\mathrm{bulge}}$ correlation. Recently, Gebhardt *et nuk.* (2000c; see Figure 6, below, for an update) have shown that reverberation mapping BH masses agree with the $M_\bullet - \sigma_e$ correlation. This suggests that the problem uncovered in previous comparisons was that the bulge luminosities of the reverberation mapping galaxies were measured incorrectly or were inflated by young stars. Gebhardt *et nuk.* (2000c) and Figure 6 here suggest that reverberation mapping does produce reliable BH masses.

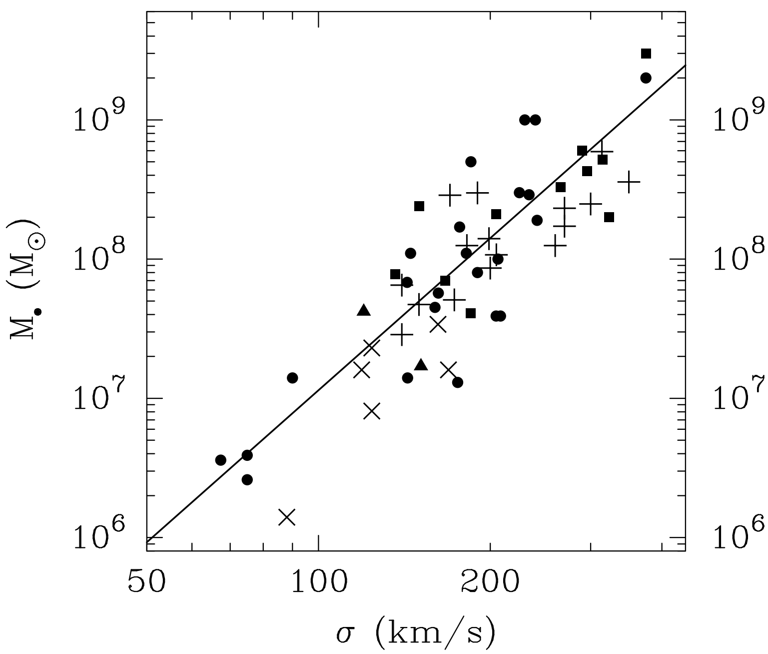

FIGURE 6. The $M_\bullet - \sigma_e$ correlation for galaxies with BH masses from detailed dynamical models applied to spatially resolved kinematics (filled symbols as in Figure 2), reverberation mapping (crosses), and ionization models (plus signs).

Similarly, ionization model BH masses – ones based on the observed correlation between quasar luminosity and the radius at which the broad-line-emitting gas lives – are largely untested and therefore uncertain. Laor (1998) and Gebhardt *et nuk.* (2001) now show that this technique also appears to produce $M_\bullet$ values with no systematic offset from other techniques (Figure 6).

These results are important because neither reverberation mapping nor ionization models require us to spatially resolve the central region affected by the BH. Both techniques can be applied to objects at arbitrarily large distances. Therefore BH masses can now be estimated for quasars out to redshifts of nearly $z = 6$. Ongoing surveys like 2dF and the Sloan Digital Sky Survey are producing thousands of quasar detections. BH masses should therefore be derivable for very large samples that span all redshifts from $z = 0$ to the most distant objects known. It will be important to check as well as possible that the physical circumstances that make the ionization models work so well are still valid far away. Nevertheless, it should be possible to directly measure the growth of BHs in the Universe.

The Effects of Black Holes on Galaxy Structure

There is other encouraging news, too. In the past, the BH search was decoupled from other galaxy studies. It was carried out largely in isolation to test the AGN paradigm. Furthermore, the early BH detections were mostly in inactive galaxies, so even the connection with AGN physics was indirect. This situation was reviewed in Kormendy & Richstone (1995). But now BH results are beginning to connect

up with a variety of work of galaxy physics. The subject is large and our space is limited. We therefore mention briefly only three of the developing results.

1 – Triaxial elliptical galaxies evolve rapidly toward axisymmetry if the central gravitational potential well gets steep enough (Lake & Norman 1983; Gerhard & Binney 1985; Norman, May, & van Albada 1985; Valluri & Merritt 1998; Merritt & Quinlan 1998; Poon & Merritt 2001; Holley-Bockelmann *et al.* 2001; see Merritt 1999 for a review). This can be achieved either by increasing the central density of stars via gas infall and star formation or by the growth of a BH. In either case, chaotic mixing of stellar orbits redistributes stars in phase space and causes orbit shapes to evolve. Box orbits, which support the triaxial structure but which allow stars to pass arbitrarily close to the center, are destroyed in favor of orbits that suppport axisymmetric structure. To the extent that triaxiality promotes gas infall and BH feeding, the evolution may also turn off the feeding when the BH has grown to 1 or 2 % of the bulge mass. These processes help to explain the observed upper limit to the BH mass fraction.

2 – Some elliptical galaxies have "cuspy cores", i. e., density distributions that break at small radii from steep outer power laws to shallow inner power laws. These cores may be produced by the orbital decay of binary BHs (Begelman, Blandford, & Rees 1980; Ebisuzaki, Makino, & Okamura 1991; Makino & Ebisuzaki 1996; Quinlan 1996; Quinlan & Hernquist 1997; Faber *et nuk.* 1997; Milosavljević & Merritt 2001). The formation of BH binaries is a natural consequence of hierarchical galaxy mergers. The orbits then decay (i. e., the binaries get "harder") by flinging stars away. This BH scouring may reduce the stellar density enough to produce a break in the density profile.

3 – Three-integral dynamical models tell us the distribution of stellar orbits around a BH. Preliminary results (van der Marel *et al.* 1998; Cretton *et al.* 1999b; Gebhardt *et nuk.* 2000a, 2001; Richstone *et nuk.* 2001) show an important difference between core and power-law galaxies. In core galaxies, the central tangential velocity dispersion σ_t is larger than the radial dispersion σ_r. Large tangential anisotropy is consistent with the effects of BH binaries (Nakano & Makino 1999a, b) and BH scouring (Quinlan & Hernquist 1997). In contrast, coreless galaxies, which have featureless, almost power-law density profiles, are observed to have $\sigma_r \simeq \sigma_t$. This is more consistent with the adiabatic growth of single BHs via gas accretion (Quinlan, Hernquist, & Sigurdsson 1995 and references therein). Further studies of the relationship between BHs and properties of their host galaxies should provide much better constraints on the relationship between BHs and galaxy formation.

The above developments are an important sign of the developing maturity of this subject. Finding convincing connections between BH properties and the microphysics of galaxies contributes in no small measure to our confidence in the BH picture. The medium-term future of this subject is therefore very promising.

In the longer-term future, the most fundamental progress is expected to come from gravitational wave astronomy. We can look forward to the true maturity of work on supermassive BHs when the Laser Interferometer Space Antenna (LISA) begins to provide a direct probe of strong gravity.

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